

Recent *Chandra* Results on AGNs & Future Prospects

Smita Mathur

The Ohio State University, 140 West 18th Ave., Columbus, OH 43210

Abstract. I review *Chandra*'s achievements in the last two years in AGN research. I concentrate on some topics of my interest; some others are reviewed in an accompanying article by K. Nandra. I comment briefly on the need to allow for the discovery space to ensure rapid progress in the field.

1. *Chandra* At Sharp Focus

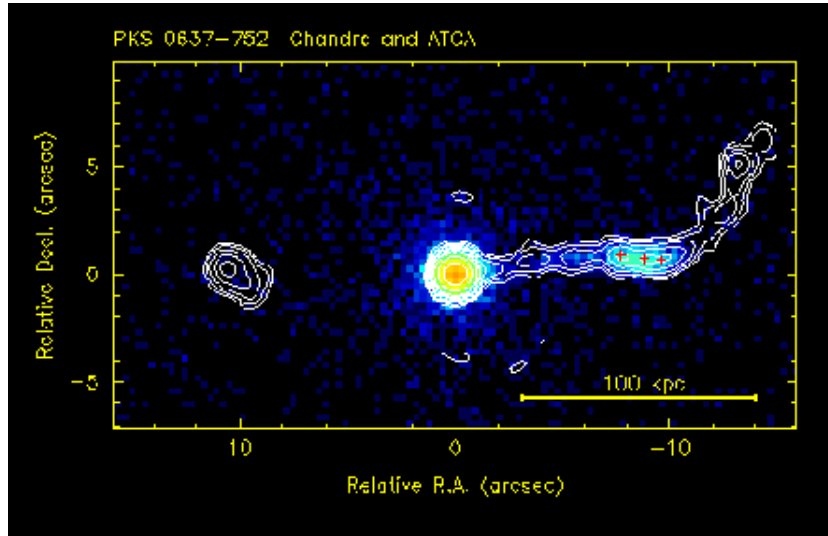
This meeting is called “*Chandra* At Sharp Focus”. So let me begin at the beginning when *Chandra* was being focused. The radio-loud quasar PKS 0637-752, known to be a “point source”, was observed to achieve the sharp focus. What was detected is shown in figure 1. The very first observation with *Chandra* led to the discovery of a 100 kpc jet in this quasar, immediately showing the unprecedented power of the observatory (Schwartz *et al.* 2000). Many more observations of X-ray jets then followed (Marshall *et al.* 2001, Sambruna *et al.* 2001). These are not just pretty pictures. Multiwavelength observations, radio–optical–X-ray, allowed determination of spectral energy distributions to constrain the emission mechanisms.

Observations revealed that the jets are complex. In most cases, the overall jet morphology in different wavebands was remarkably similar (fig. 1), but there were subtle differences. In some cases (e.g. 3C 273), simple Synchrotron models provide good fit to the data, but in some cases they do not. In PKS 0637-752, Synchrotron self-Compton models imply extreme departure from equipartition of magnetic and particle energy, while the models invoking the inverse-Compton of microwave background photons require large Doppler factors ($\delta \sim 10$, Tavecchio *et al.* 2000).

Because of these complexities, the new *Chandra* observations are often viewed as posing problems to our understanding of jet physics. I do not view them as problems; they in fact offer opportunities to understand particle acceleration and magnetic field structure. In this respect it is instructive to see what Begelman, Blandford and Rees wrote in 1984: “With AXAF (now renamed *Chandra*), it should be possible to detect X-ray emission from several more jets.it will then be possible to make improved estimates of the magnetic field strengths, and so test the equipartition hypothesis”. I think the important word here is “test”.

From this demonstration of the excellent imaging capability of *Chandra*, now I will move on to science exploiting its unprecedented spectroscopic quality.

Figure 1. *Chandra* image of the X-ray jet in PKS 0637-752 (from Schwartz *et al.* 2000). Radio contours are overlaid on the X-ray image.

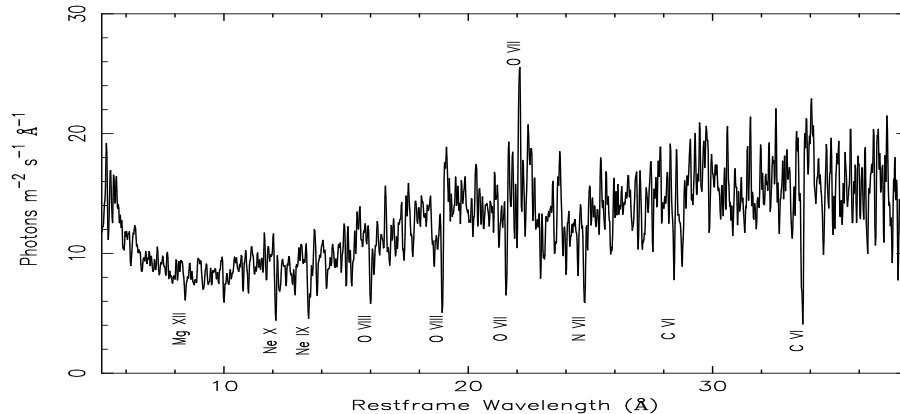


2. Warm Absorbing Outflows in AGNs

2.1. Pre-*Chandra* Era

Absorption edges due to OVII/OVIII were detected in several AGNs with ROSAT (e.g. Fiore *et al.* 1993) and ASCA (e.g. George *et al.* 1998). Associated UV absorption lines due to OVI, CIV, NV and Ly α were also detected in several AGNs (e.g. Bahcall *et al.* 1993). In Seyfert galaxies, one-to-one correspondence was observed between the UV and X-ray absorbers (Crenshaw & Kraemer 1999). Photoionization models then allowed determination of physical conditions in the absorbing gas. Over the years (1994–2001), Mathur & collaborators have argued that the X/UV absorber must be highly ionized, high column density, outflowing gas located at/outside the broad emission line region of AGNs. Note that the information that the X-ray warm absorbing gas is “outflowing” came only with its association with the UV absorber. The important point is that over a range of parameters, a photoionized plasma would imprint signatures in both X-ray and UV bands. Obviously, if the gas is too highly ionized, there may not be detectable UV absorption lines and if the gas has too low column density then there would not be any detectable X-ray absorption. Complexity, as commonly seen in UV absorption systems is also expected in X-ray warm absorbers (see Mathur 1997 and references there in). Understanding the physical conditions in warm absorbers is important because the outflow seems to carry a significant amount of kinetic energy and the mass outflow rate, in many cases, is comparable to the accretion rate needed to power the AGN (Mathur *et al.* 1995).

Figure 2. LETG/HRC Spectrum of NGC 5548 (from Kaastra *et al.* 2000).



2.2. Warm Absorber models: Predictions

The above understanding of the physical conditions in the warm absorbers led to following predictions. 1) In addition to the edges, resonance absorption lines due to highly ionized elements should also be present (Nicastro *et al.* 1999). 2) The X-ray absorption lines should show blue-shifts, similar to those in the UV lines. 3) FWHM of X-ray lines should match the UV lines. 4) The column densities of ions derived from the X-ray and UV lines should match. Again, because of the exceptions discussed above, not *every* absorption system in X-rays would have a match in the UV and vice-a-versa.

2.3. Chandra Observations of Warm Absorbers

High resolution spectroscopy of AGNs known to have warm absorbers, was performed in the first two years of *Chandra*. Below I review four such cases.

NGC 5548: This well studied AGN was observed with LETG/HRC. Figure 2 shows the rich absorption line spectrum. Strong, narrow absorption lines from highly ionized species are clearly present (Kaastra *et al.* 2000). The widths of the X-ray lines are consistent with the UV lines. The average blueshift of the X-ray absorption lines was found to be somewhat smaller, but comparable to the UV lines. However, further relation between the X-ray and UV absorbers remained an open issue because of the low S/N and lower resolution of the X-ray spectrum. (The spectral resolution of LETG is ~ 300 – 1000 compared to $\sim 10,000$ of HST/STIS in medium resolution.)

NGC 3783 was observed with HETG/ACIS-S (Kaspi *et al.* 2000, 2001). The high resolution spectrum revealed the presence of narrow absorption lines of H- and He-like ions of O, Ne, Mg, Si, S and Ar as well as FeXVII–FeXXI L-shell lines. These observations showed that the warm absorber is indeed outflowing

with blueshifts of the lines consistent with the UV lines. The velocity dispersion was also found to be consistent with the UV lines. In the first paper (2000) the authors claimed that the column densities of X-ray and UV absorption lines do not match. This was a surprise given the consistency of Chandra and ASCA observations and the excellent ASCA/UV match shown by Shields & Hamann (1997). The predicted UV line strengths are highly sensitive to the assumed continuum shape in the unobservable EUV range. Indeed, in the second paper (2001), the authors found this sensitivity to be case and the column densities predicted from the low-ionization component were consistent with the UV lines, given a particular EUV slope.

NGC 4051: This narrow line Seyfert 1 galaxy was observed simultaneously with *Chandra* (HETG/ACIS-S, spectral resolution ~ 1000) and HST (STIS) (Collinge *et al.* 2001). The authors have done an excellent job of analyzing the data and have been careful in their interpretation. Again, a number of absorption lines were detected. Photoionization modeling revealed two separate components: a high ionization system with high outflow velocity and a low ionization system with low velocity. The UV observations also detected absorption lines, as expected, with multiple velocity components. The low-velocity X-ray absorption is consistent in velocity with many of the UV systems, but the high velocity X-ray absorption does not seem to have any UV component. The authors point out that X-ray spectroscopy with even higher resolution (matching that of STIS) may show multiple components in X-ray lines as well.

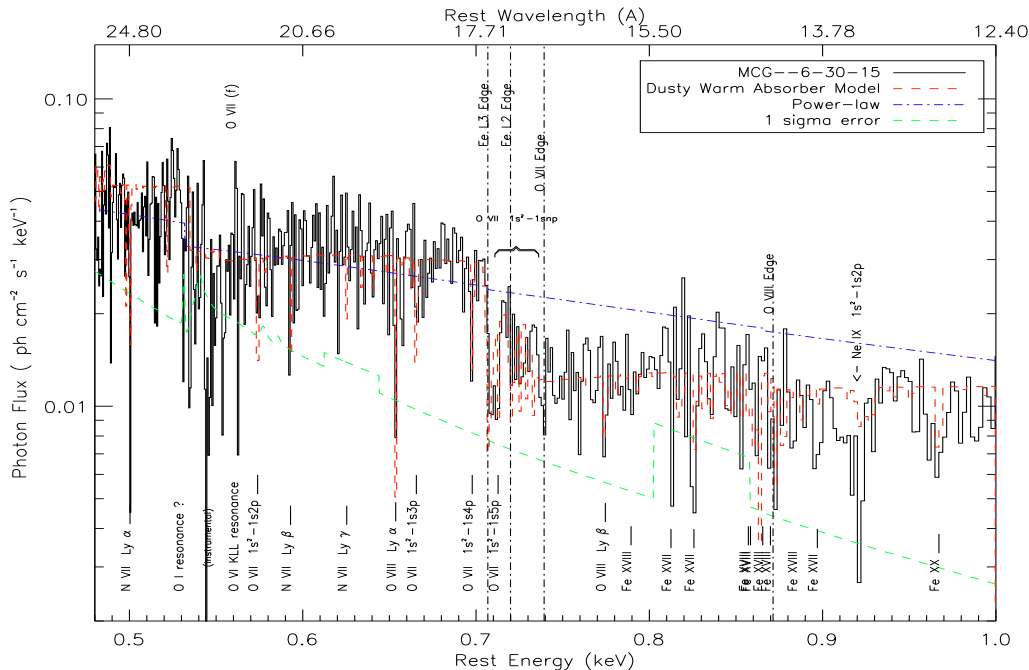
MCG-6-30-15: This AGN, well-known from ASCA for its broad Fe K α line, was known to harbor a warm absorber with possibly two components (Reynolds *et al.* 1995). XMM-Newton RGS observations of this source, however, lead Branduardi-Raymont *et al.* (2001) to propose a radically alternative explanation for the soft X-ray features. These authors claimed that there is no warm absorber in MCG-6-30-15, and the soft X-ray features are best explained by relativistically broadened emission lines. The higher resolution *Chandra* HETG/ACIS-S observation, therefore, were particularly interesting and demonstrated the superior quality of *Chandra* gratings. The *Chandra* observations detected a numerous absorption lines due to highly ionized species of a number of elements (Figure 3). In a detailed analysis, Lee *et al.* (2001) showed that a warm absorber model is not only adequate for MCG-6-30-15, the data require it. These observations also revealed first clear detection of OVI KLL resonance absorption, recently predicted by Pradhan (2000). It is interesting too see how the progress in high resolution X-ray spectroscopy is going hand in hand with atomic physics.

Thus, all the above observations of warm absorbers have shown consistency with the model predictions (§2.2) based on a common origin of the X-ray and UV absorbing gas.

3. Broad Absorption Line Quasars (BALQSOs)

The UV properties of BALQSOs are similar to the associated absorption systems discussed above, except that their absorption lines are very broad, with

Figure 3. HETG/ACIS-S Spectrum of MCG-6-30-15 with a warm absorber model overplotted (from Lee *et al.* 2001).

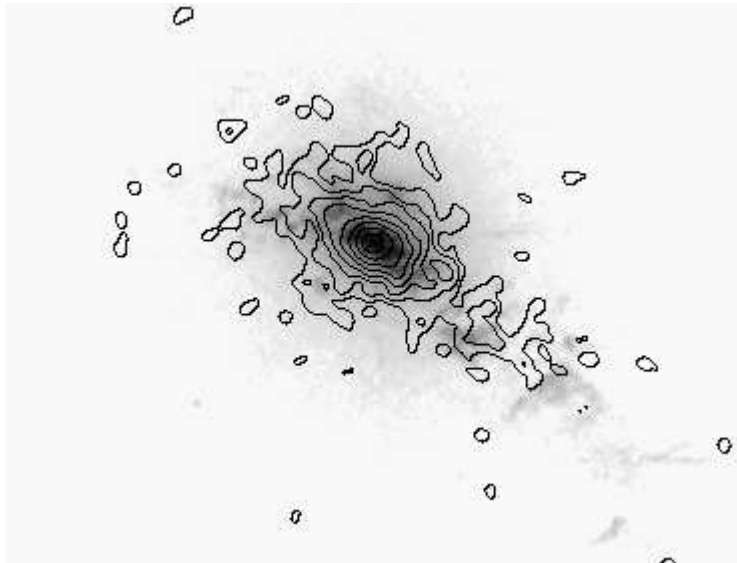


terminal outflow velocities up to $0.1c$. Therefore it is very important to understand the physical conditions in the absorbing gas as the outflow might imply an energy budget problem. The physical conditions are poorly constrained by the UV line studies alone and X-ray spectra would potentially provide complementary information as demonstrated by the X/UV absorbers discussed above. However, BALQSOs are markedly underluminous in soft X-rays, with most observations resulting in non-detections. Recent studies (Mathur *et al.* 2000, 2001, Gallagher *et al.* 2001a and references there in) imply that the BALQSOs are not intrinsically X-ray weak, but the strong absorption makes them appear faint. In some cases there is clear evidence of partial covering by the absorber and at least in one case there is indication of a steep X-ray power-law slope. If true, this is extremely important as it bears on the evolutionary scenarios of quasars (Mathur 2000).

3.1. *Chandra* observations of BALQSOs

The sharp point spread function and very low background of *Chandra* make it ideal for detecting faint point sources like BALQSOs. We carried out a snapshot survey of 10 BALQSOs with *Chandra*, and detected 8 of them (Green *et al.* 2001). Each source had too few counts to do meaningful spectroscopy, so a composite spectrum was generated by stacking them all together. The best fit model was an absorbed power-law ($N_H = 2-10 \times 10^{22} \text{ cm}^{-2}$) partially covering the source. The best fit slope is similar to that of non-BAL radio-quiet quasars,

Figure 5. Extended soft X-ray emission along the ionization cone in NGC 4151 (from Ogle *et al.* 2000). *Chandra* contours are overlayed on an HST [OIII] 5007 image.

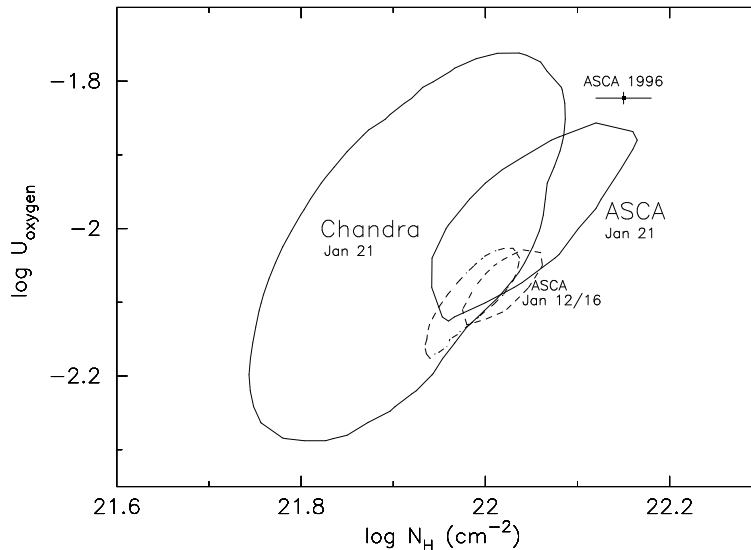


ally ionized gas. As such, the plasma characteristics are consistent with a warm absorber seen in emission. Another noteworthy result from this observation is the detection of extended soft X-ray emission in the direction of ionization cones. This soft emission is consistent with that due to recombination from a photoionized plasma.

NGC 4151: The HETG/ACIS-S observation of this Seyfert 1.5 galaxy is reported by Ogle *et al.* (2000). Here again, extended soft X-ray emission along the ionization cone is observed (Figure 5) and numerous emission lines are detected. However, the characteristics of the emission line plasma seem to be different from that in Mrk 3. The relative strengths of resonance and forbidden lines in the OVII and NeIX triplet are different. This fact, together with other features led the authors to conclude that the emission line plasma is made of at least two distinct components: one hot, collisionally ionized and other cooler, photoionized medium. The hot plasma can pressure confine the cooler clouds. A large fraction of the emission line flux seems to come from the extended emission on the scales of the narrow emission line region. This appears to be the case even for the Fe-K α line! More discussion of Fe-K lines is presented in K. Nandra's article.

The extended emission, discussed above, was known previously from *Einstein* HRI and ROSAT HRI observations (e.g. NGC 4151: Elvis, Briel & Henry 1983; Mrk 3: Morse *et al.* 1995). However, the *Chandra* images are spectacularly better and the additional spectral information allows determination of physical conditions in the extended material. See also Young *et al.* (2001) for *Chandra* observation of extended emission in NGC 1068.

Figure 6. Comparison of confidence contours of the derived quantities from *Chandra* and ASCA data of NGC 3783 (from Kaspi *et al.* 2001).



5. What have we learned and Where are we going?

The data on AGNs accumulated over the first two years of *Chandra* are beautiful! They show the power of the observatory both in extraordinary imaging and high resolution spectroscopy. And they are not just pretty pictures, or spectra. They can be tremendously useful in gaining insights on AGN physics. However, most of the targets are under-exposed, as is usually the case in the first year or two of observations with a new mission. As a result, most of the absorption line spectra have low signal to noise ratio (S/N): the measured absorption line equivalent widths are uncertain to $\pm 40\%$. So the keyword here is CAUTION. Figure 6 (from Kaspi *et al.* 2001) is instructive: it shows that errors on derived parameters (ionization parameter and column density in this case) from *Chandra* data are in fact much larger than those from ASCA data! This clearly demonstrates the S/N problem. So many of the spectra discussed above should be viewed more as a proof of concept than diagnostic tools. Moreover, most of the modeling efforts are preliminary. So once again, the keyword is CAUTION, especially if the results are unexpected. Only when we obtain well constrained parameters can we hope to build and test models of AGN structure and physics. One such effort is lead by Ian George in obtaining multiwavelength, high S/N spectra of a nearby Seyfert galaxy with a warm absorber. The team has observed NGC 3783 with HETG/ACIS-S for 900 ksec. This is the largest exposure for high resolution spectroscopy of any target. Many more are sure to come in next *Chandra* cycles.

However, over-emphasis on details often deprives us from having some discovery space. We heard from the talks in other fields (e.g. galaxies, c.f. A. Prestwich's article) that their approach was far more exploratory. It is no sur-

prise then that the results were unexpected. If we do not allow for discovery space in AGN research, we will have to depend upon serendipity for surprises and may be even for rapid progress. Let me discuss just one example. One of the interesting results on quasars (and there are many more; some discussed by K. Nandra) has come from the deep field observations. Barger *et al.* (2001) concluded that the quasar life times are about half a Gyr, much larger than generally thought (incidentally, these large times are similar to what we found based on black-hole mass to bulge mass relation of narrow line Seyfert 1 galaxies (Mathur, Kuraszekiewicz & Czerny 2001)). Quasar life times are intimately related to the space density of quasars and to the question of whether or not quasars are integral part of the life of a galaxy. Only when we understand evolution of quasars, will we be able to give them their rightfully important place in cosmology.

6. Quasars as Distant Light Beams

I will now briefly touch upon a different aspect of quasar observations: not to study the quasars themselves but to use them as distant light beams to look for the matter between us and the quasar. So this is truly taking an “X-ray” of the Universe in between. K. Nandra has already talked about observing the Damped Lyman-alpha systems in the line of sight to high redshift quasars. I will discuss the attempts to detect the warm-hot intergalactic medium (IGM) with *Chandra*.

The theory of big-bang nucleosynthesis together with the estimates of deuterium abundance, imply a baryon density parameter $\Omega_b = 0.04h_{70}^{-2}$ (Burles & Tytler 1998). At high redshift, it appears that most of these baryons reside in the diffuse IGM and have been detected by Ly α forest absorption in background quasars (e.g. Weinberg *et al.* 1997). At low redshift, however, Ly α forest absorption is not observed. The baryons in the stellar and gaseous components of galaxies add up to $\Omega_b = 0.004h_{70}^{-1}$ and hot gas in clusters of galaxies makes similar contribution to Ω_b . So most of the low redshift baryons seem to be missing.

Hydrodynamic cosmological simulations predict that a large fraction of low redshift baryons still reside in IGM, shock heated to high temperatures (10^5 – 10^7 K; Cen & Ostriker 1999), where it produces very little hydrogen absorption. So the most promising, and perhaps the only way to trace the warm-hot IGM is via the “X-ray forest” of high excitation metal lines (e.g. Hellston *et al.* 1998). For the first time in X-ray astronomy, the *Chandra* gratings have enough resolution to study the narrow, intervening absorption lines in quasars, a major field of research that has previously been the sole preserve of optical/UV astronomy.

Fang *et al.* (2001) made attempts to detect the warm-hot IGM in the line of sight to two distant quasars with HETG. These observations did not lead to detections of intervening absorption lines. We recently observed a nearby bright quasar H1821+643 for 500 ksec with LETG/ACIS-S. With these observations, we expect to make the first detection of warm-hot IGM and even the non-detection would lead to meaningful constraints on its temperature range. So stay tuned.....

It is my pleasure to thank the entire *Chandra* team for a wonderful mission, to the organizing committee for inviting me, and to the authors of all the papers which I have reported here. Because of the constraints on space & time, I could report on only a few topics and refer to papers by only a few authors. My apologies to everybody else.

References

- Bahcall, J.N. *et al.* 1993, ApJS, 87, 1
 Begelman, M., Blandford, R., & Reed, M. 1984, Rev. Mod. Phys., 55, 255
 Barger, A., *et al.* 2001, AJ, submitted.
 Branduardi-Raymont, G. *et al.* 2001, A&A Lett., 365, 140
 Burles, S. & Tytler, D. 1998, ApJ, 499, 699
 Cen, R. & Ostriker, J.P. 1999, ApJ, 514, 1
 Collinge, M. *et al.* 2001, ApJ, in press
 Crenshaw D.M. & Kraemer S.B., 1999, ApJ, 321, 233
 Elvis, M., Briel, U. & Henry, P. 1983 ApJ 268, 105
 Fang, T., Marshall, H., Bryan, G., Canizares, C. 2001, ApJ, 555, 356
 Fiore, F., Elvis, M., Mathur, S., Wilkes, B., & McDowell, J. 1993, ApJ, 415, 129
 Gallagher, S. *et al.* 2001, ApJ, 546, 795
 Gallagher, S. *et al.* 2001, in “Mass Outflow in AGN: New Perspectives”, ASP Conference Series, eds. D. M. Crenshaw, S. B. Kraemer, and I. M. George
 George, I. *et al.* 2000, ApJ, 531, 52
 Green, P.J. *et al.* 2001, ApJ, in press
 Hellsten, U., Gnedin, N.Y. & Miralda-Escudé, J. 1998, ApJ, 509, 56
 Kaastra, J. *et al.* 2000, A&A Lett., 354, 83
 Kaspi, S. *et al.* 2000, ApJL, 535, 17
 Kaspi, S. *et al.* 2001, ApJ, 554, 216
 Krolik, J. & Kriss, G. 1995, ApJ, 447, 512
 Lee, J., *et al.* 2001, ApJL, 554, 13
 Marshall, H. L. *et al.* 2001, ApJL, 549, 167
 Mathur, S., Elvis, M. & Wilkes, B. 1995 ApJ, 452, 230
 Mathur, S. 1997 in “Mass Ejection from AGN”, Ed: N. Arav, I., Shlosman, & R. Weymann [ASP Conf. Series Vol. 128]
 Mathur, S. 2000, MNRAS Lett., 314, 17
 Mathur, S. *et al.* 2000, ApJL, 533, 79
 Mathur, S. *et al.* 2001, ApJL, 551, 13
 Mathur, S., Kuraszewicz, J., & Czerny, B. 2001, NewA, 6, 321
 Morse, J. *et al.* 1995, ApJ, 439, 121
 Nicastro, F., Fiore, F. & Matt, G. 1999, ApJ, 517, 108
 Ogle, P. *et al.* 2000, ApJ, 545, 81
 Pradhan, A. 2000, ApJL, 545, 165

- Reynolds, C. *et al.* 1995 MNRAS, 277, 901
- Sambruna, R. M. *et al.* 2001, ApJ, 549, 161
- Sako, M., Kahn, S.M., Paerels, F., Liedahl, D. 2000, ApJL, 543, 115
- Schwartz, D. A. *et al.* 2000, ApJL, 540, 69
- Shields. J. & Hamann, F. 1997, ApJ, 481, 752
- Tavecchio, F., Maraschi, L., Sambruna, R., Urry, C.M. 2000, ApJ, 544, 23
- Weinberg, D.H., Miralda-Escudé, J., Hernquist, L., & Katz, N., 1997, ApJ, 490, 564